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A promising approach to detecting roadside bombs attached to command wires is the electromagnetic sensing and identification of the wires. The lowest five resonant frequencies of the wires, along with the widths of the resonances, can serve as a "fingerprint" for finding the wires. A first major step toward exploiting this fingerprint is to calculate the resonances and their widths for a straight wire on a flat interface between a homogeneous earth and air. The calculation of resonances requires extending the theory of the linear antenna to deal with a wire on the

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Final Report on Research in Support of Electromagnetic Detection and Jamming of Improvised Explosive Devices

ABSTRACT

A promising approach to detecting roadside bombs attached to command wires is the electromagnetic sensing and identification of the wires. The lowest five resonant frequencies of the wires, along with the widths of the resonances, can serve as a "fingerprint" for finding the wires. A first major step toward exploiting this fingerprint is to calculate the resonances and their widths for a straight wire on a flat interface between a homogeneous earth and air. The calculation of resonances requires extending the theory of the linear antenna to deal with a wire on the interface between two dielectric media, which we accomplish here. Complex-valued resonant frequencies are defined as those for which a certain homogeneous integral equation for the current in the wire on the interface has non-trivial solutions. By applying a Galerkin procedure we obtain approximate numerical solutions for the resonant frequencies and their widths.

We also discuss antenna structures needed to implement an electromagnetic sensor to exploit the resonances for the detection and identification of command wires and give pointers to published material relevant to the analysis of health effects of exposure to electromagnetic radiation.

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Tai Wu	0.08	No
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Final Report

on

Research in Support of Electromagnetic Detection and Jamming of Improvised Explosive Devices

submitted by

Sheldon S. Sandler, John M. Myers, and Tai Tsun Wu (PI)

for

Army Research Office Grant W911NF-07-1-0509

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Final Report on

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November 15, 2009

Abstract—A promising approach to detecting roadside bombs attached to command wires is the electromagnetic sensing and identification of the wires. The lowest five resonant frequencies of the wires, along with the widths of the resonances, can serve as a "fingerprint" for finding the wires. A first major step toward exploiting this fingerprint is to calculate the resonances and their widths for a straight wire on a flat interface between a homogeneous earth and air. The calculation of resonances requires extending the theory of the linear antenna to deal with a wire on the interface between two dielectric media, which we accomplish here. Complex-valued resonant frequencies are defined as those for which a certain homogeneous integral equation for the current in the strip on the interface has non-trivial solutions. By applying a Galerkin procedure we obtain approximate numerical solutions for the resonant frequencies and their widths.

We also discuss antenna structures needed to implement an electromagnetic sensor to exploit the resonances for the detection and identification of command wires and give pointers to literature relevant to the analysis of health effects of exposure to electromagnetic radiation.

FORWARD

Two years ago we began to work on the problem of detecting and identifying improvised explosive devices (IEDs). Our approach was to find electromagnetic characteristics visible to an electromagnetic sensor, based on transmitting suitable electromagnetic radiation and receiving an echo. Early on it became apparent that IEDs come in such a variety of forms that it would be difficult or impossible to find a characteristic signature for an IED by itself; however, we learned that many IEDs are detonated by means of command wires that run on or near the earth surface for a 100 meters or more. Such command wires must have resonant frequencies at which they produce particularly strong echoes. Such resonances shift when the command wires change length, but the ratio of the resonant frequencies to the frequency of the first resonance is expected to be constant. For this reason the ratios of resonant frequencies along with the widths of the resonances can serve as a fingerprint by which to detect and identify command wires that control roadside bombs.

We undertook the first step of studying these resonances. We simplified the problem as much as we could by restricting ourselves to the artificial case in which the wires are straight, close together, and on the interface between a homogeneous flat earth and air. Even with these restrictions, the problem of determining resonant frequencies of a wire on an earth-air interface is a challenge. Fortunately, we had a starting point in our past work on studying electromagnetic radiation not in free space, as is usually the case for theoretical work, but near an interface between two media [1]. Here are reported:

1. The desired fingerprint of resonances for a straight wire (or wire pair) on a flat earth.

2. Suggestions concerning antennas suitable for transmitting signals and detecting echoes at frequencies appropriate for the predicted resonances

3. Advances in techniques for studying electromagnetic radiation near an interface.

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I. STATEMENT OF PROBLEM STUDIED

The main problem studied here is the determination of an electromagnetic signature—"fingerprint"—that can help with the detection and identification of command wires that control roadside bombs. We use the Maxwell equations that define electromagnetism to analyze a straight thin wire (or wire pair) on a flat interface between earth and air or, more generally, between two homogeneous media, each characterized by a given dielectric constant. In the simpler case of a homogeneous medium, electromagnetic scattering by a wire is insensitive to the shape of the cross section of the wire. For example, with perfect conductors, a wire consisting of a flat strip of width $4a$ and negligible thickness is electromagnetically essentially the same as a circular wire of radius a. This insensitivity holds also for a thin wire or wire pair on the boundary between two different dielectric media, and for analytical convenience we analyze a flat, perfectly conducting strip of length $2h$, width $4a$, and zero thickness. We assume the strip is located in a plane interface, thought of as horizontal, between a medium below (earth) with a dielectric constant k_1 and a medium above (air) with a propagation constant $k_2 = 2\pi f/c$ where f is the frequency of the electromagnetic radiation in Hertz and $c \approx 3 \times 10^8$m/s is the speed of light. The main task is to find the first five resonant frequencies for electromagnetic radiation scattered by this thin strip as functions of the parameters a, h, k_1, and k_2; the width of each resonance is also to be determined.

We also discuss antenna structures needed to implement an electromagnetic sensor to exploit the resonances for the detection and identification of command wires and give pointers to published material relevant to the analysis of health effects of exposure to electromagnetic radiation.

II. SUMMARY OF THE MOST IMPORTANT RESULTS

The following results were obtained:

1. Numerical values for the first five resonant frequencies and their widths, similar to phenomena in an ordinary RLC resonant circuit, discussed in the accompanying Technical Report [2], which covers:

   (a) Expression of the electric field $E_x(x, y)$ along the strip generated by a current element on the strip, obtained as the inversion of a Fourier transform. This expression lays the groundwork for a kernel in an integral equation.

   (b) Finding the complex-valued zeros in the Fourier transform of $E_x(x, y)$ with respect to x, denoted $\tilde{E}_x(\zeta, y)$. These zeros play a role similar to the zeros in the Fourier transform for the homogeneous case, and in the same way they allow one to obtain an integral equation of the Pocklington type for the current in the strip.

   (c) Derivation of the integral equation for the current in a thin strip on the interface.

   (d) Definition of the complex-valued resonant frequencies as the frequencies at which the homogeneous integral equation for the current in the strip on the interface has non-trivial solutions.

   (e) Approximate equations for the resonant frequencies, suitable for numerical calculation, obtained using a Galerkin procedure.

   (f) Numerical solutions for the first five resonant frequencies defined by the homogeneous integral equation, along with the width of each resonance, (which is simply related to the imaginary part of the complex-valued resonant frequency).

2. Considerations of antenna structures needed to implement an electromagnetic sensor to exploit the resonances for the detection and identification of command wires are discussed in Appendix B.

3. Pointers are given in Appendix C to material relevant to the analysis of health effects of exposure to electromagnetic radiation.

Example: For the case of earth having a *relative* dielectric constant $\epsilon_r = \epsilon_1/\epsilon_2 = 4$, the ratio of propagation constants is $k_1/k_2 = 2$. The accompanying Technical Report [2] gives the first five complex-valued resonant frequencies for three cases of h/a, the ratio of wire length to wire thickness, are given in Table 1.

TABLE 1:   Complex values of $k_2 h$ at resonance n

n	$h/a = 10^4$	$h/a = 10^5$	$h/a = 10^6$
1	0.956824-i0.047401	0.965436-i0.038153	0.970820-i0.031885
2	1.934017-i0.079959	1.947398-i0.063718	1.955503-i0.052866
3	2.905922-i0.115751	2.925628-i0.091953	2.937355-i0.076062
4	3.872673-i0.153152	3.900158-i0.121734	3.916394-i0.100618
5	4.837435-i0.190228	4.873157-i0.151508	4.894259-i0.125246

(The propagation constant in air is $k_2 = 2\pi f/c$, where f is the frequency of the electromagnetic radiation in Hertz. Note that an even resonance number n corresponds to anti-resonance for the impedance of a center-driven antenna.)

Figures 1, 2, and 3 show the resonances implied by Table 1 as a function of frequency for the three cases of h/a of 10^4, 10^5 and 10^6, respectively. For each case, the corresponding figure shows the real part (solid lines) and the imaginary part (dashed lines) of $\dfrac{1}{k_2 h - (k_2 h)_{n\text{-th res}}}$ for the first five resonances, where $(k_2 h)_{n\text{-th res}}$ is the n-th resonance value $(n = 1, 2, \ldots 5)$ from Table 1. These resonances were calculated using the thorough and rather complicated analysis described in Ref. [2]. A rough and ready approximation to resonant frequencies is sketched in Appendix A. Considerable future work is required to acquire the following valuable information:

1. Determine the degree to which ratios of resonant frequences are sensitive to roughness of the ground.

2. Determine the effect on resonances of wire curvature.

3. Determine the effect on resonances of vertical meanders of a wire above and below ground.
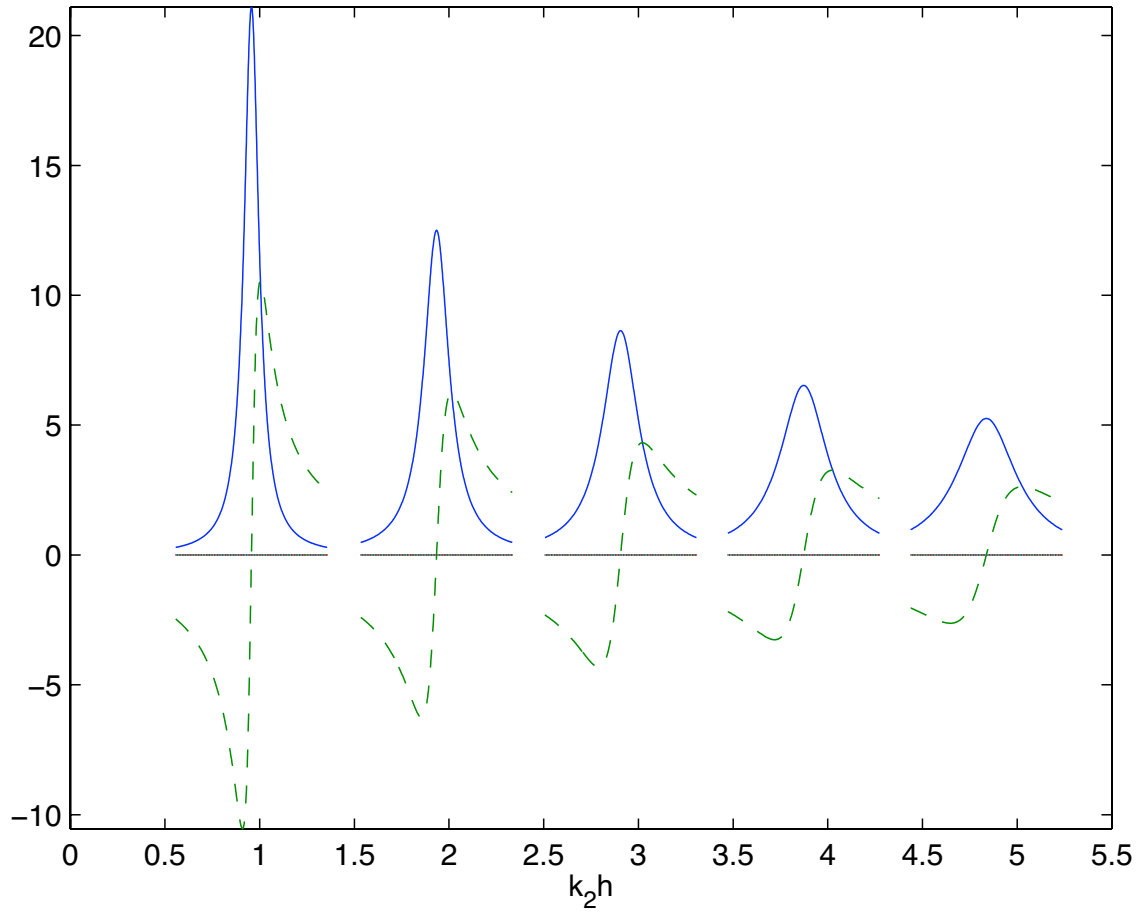
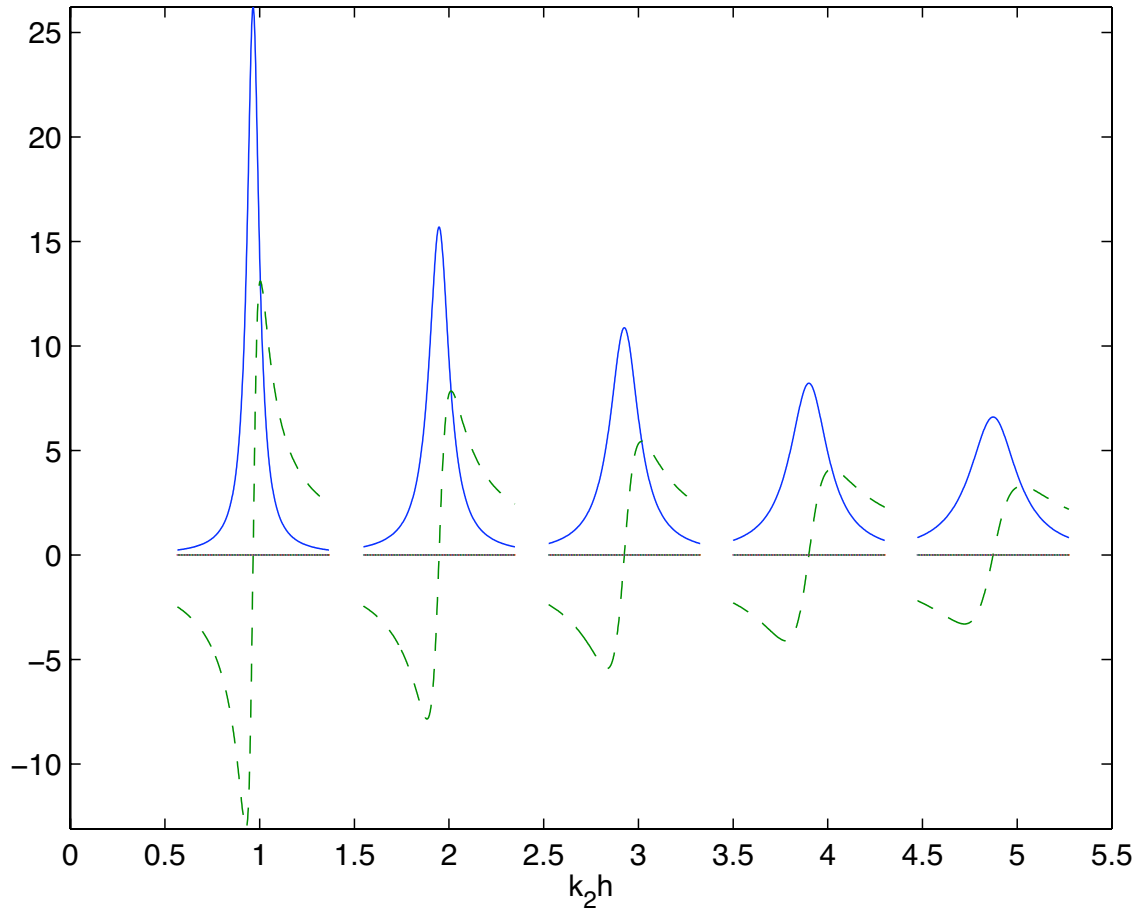FIG. 1: Resonant scattering from wire; $\epsilon_r = 4$, $h/a = 10^4$.

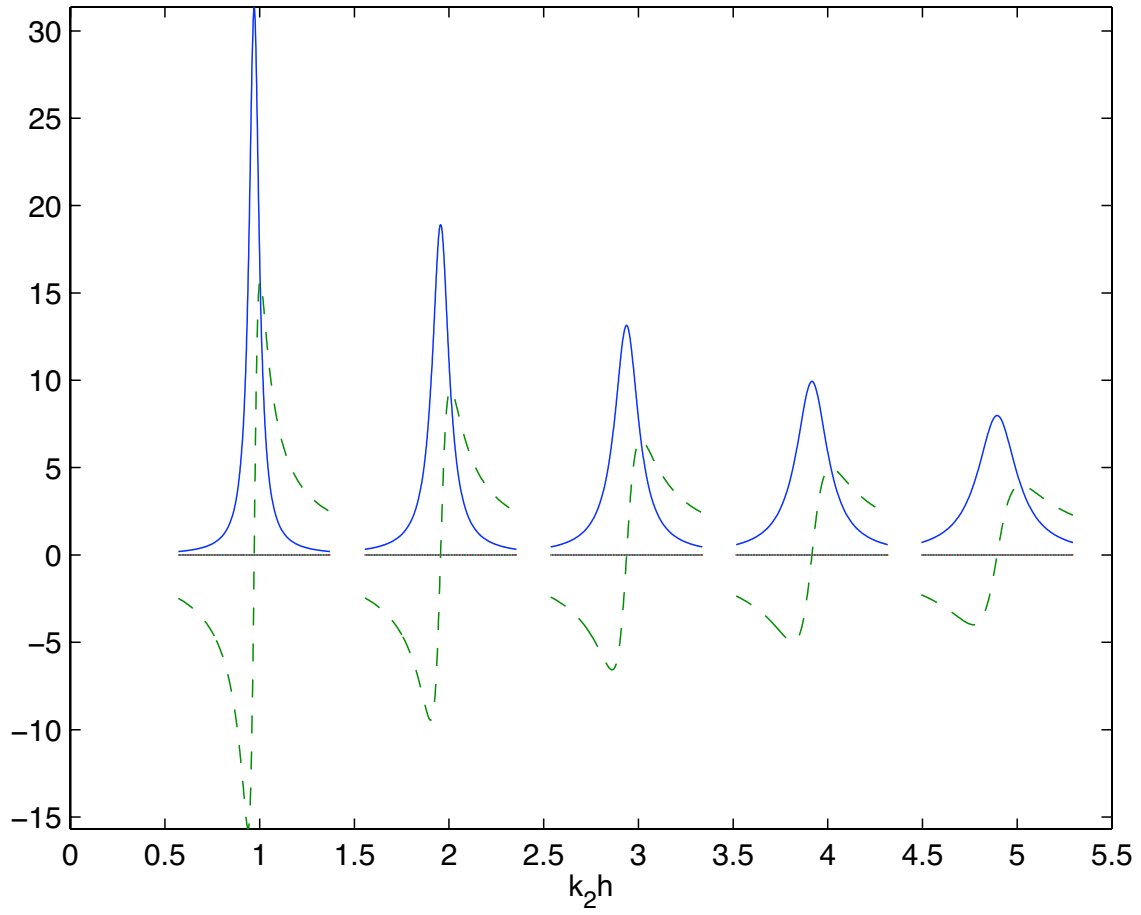FIG. 2: Resonant scattering from wire; $\epsilon_r = 4$, $h/a = 10^5$.

FIG. 3: Resonant scattering from wire; $\epsilon_r = 4$, $h/a = 10^6$.

APPENDIX A: APPROXIMATE VALUES FOR THE RESONANT LENGTHS OF A CYLINDRICAL ANTENNA: CASES OF ANTENNA IN FREE SPACE AND ON EARTH-AIR INTERFACE

The following is a much less accurate approach to resonant frequencies than that given in [2], but it has the advantage of being brief and gives a general indication of resonances expected.

Consider a linear antenna of radius a and length $2h$ along the segment $(-h, h)$ of the z-axis. The well-known electromagnetic field (EMF) method [3] relates the radiated power of the antenna to its electric circuit equivalent, so that the antenna driving-point impedance Z_0 is given by

$$Z_0 = -\frac{1}{|I_0|^2} \int_{-h}^{h} E_z I_z^* \, dz. \tag{A1}$$

In the usual application of the EMF method, one assumes a sinusoidal current I_z, ignoring the boundary condition on the tangential component of the electric field, E_z. Near resonance, the exact current is close to sinusoidal, and the assumption of a sinusoidal current implies an electric field having a near-zero tangential component along the antenna, as it should. For this reason the approximation works well, and the resulting values of the driving-point impedance and the resonant lengths are adequately accurate (except for the impedance for antenna lengths that are nearly anti-resonant, *i.e.* $kh \approx n\pi/2$ with n even). In particular, values of Z_0 near resonance ($kh \approx n\pi/2$ with n odd) are well approximated.

The extension of the EMF method to a linear antenna over the earth is based on using a zeroth-order result for the propagation constant along the wire [4] or

$$k_0 = \sqrt{\frac{k_1^2 + k_2^2}{2}}, \tag{A2}$$

where k_1 is the propagation constant for earth and k_2 is the propagation constant for free space.

In terms of tabulated integrals [5] the value of Z_0 is given for free space by

$$\begin{aligned} Z_0 = &-i \frac{\zeta_0}{2\pi} \frac{1}{\sin^2 k_0 h} \big\{ \sin k_0 h [C_a(h, h) - \cos k_0 h \, C_a(h, 0)] \\ &- \cos k_0 h [S_a(h, h) - \cos k_0 h \, S_a(h, 0)] \big\}, \end{aligned} \tag{A3}$$

where

$$C_a(h,h) \;=\; \int_{-h}^{h} dz' \cos k_0 z' \, \frac{e^{ik_0 R_1}}{R_1} \;=\; \int_{0}^{h} dz' \cos k_0 z' \left[\frac{e^{ik_0 R_1}}{R_1} + \frac{e^{ik_0 R_2}}{R_2} \right], \qquad \text{(A4)}$$

$$S_a(h,z) \;=\; \int_{-h}^{h} dz' \sin k_0 |z'| \, \frac{e^{ik_0 R_1}}{R_1} \;=\; \int_{0}^{h} dz' \sin k_0 z' \left[\frac{e^{ik_0 R_1}}{R_1} + \frac{e^{ik_0 R_2}}{R_2} \right], \qquad \text{(A5)}$$

with $R_1 = \sqrt{(z - z')^2 + a^2}$ and $R_2 = \sqrt{(z + z')^2 + a^2}$.

Sample calculations for the EMF method

TABLE 2. Resonant electrical lengths $(kh)_{\text{res}}$ for antenna in free space (dielectric constant is ϵ_0); $h/a = 10^4$. Results obtained using Galerkin [6] and EMF [3] methods.

Resonance n	$(kh)_{\text{res}}$ (Galerkin)	$(kh)_{\text{res}}$ (EMF)
1	1.5221	1.5304
3	4.6523	4.6657
5	7.7902	7.8050

TABLE 3. Resonant electrical lengths $(k_2 h)_{\text{res}}$ for antenna on earth-air interface (ϵ_1 is dielectric constant of earth). Relative dielectric constant $\epsilon_r = \epsilon_1/\epsilon_2 = 4$; $h/a = 10^4$. Results obtained using Galerkin [6] and EMF [3] methods.

Resonance n	$(k_2 h)_{\text{res}}$ (Galerkin)	$(k_2 h)_{\text{res}}$ (EMF)
1	0.9654	0.9679
3	2.9253	2.9508
5	4.8713	4.9363

The zeroth-order propagation constant is

$$k_0 \approx \sqrt{\frac{k_1^2 + k_2^2}{2}} = \sqrt{\frac{\epsilon_1 + 1}{2}} \, k_2 = 1.5811 k_2. \qquad \text{(A6)}$$

APPENDIX B: TRANSMITTING AND RECEIVING ANTENNAS FOR DETECTION AND JAMMING

In thinking about suitable antennas for the broad-band radiation to cover the first five electromagnetic resonances of command wires, we began with a transverse electromagnetic (TEM) horn. An increase in the low-frequency behavior for the TEM horn is desirable. One early thought was to use a TEMR (Transverse Electro Magnetic Rhombic) horn antenna as a basis for the design. It was designed by one of the investigators [7]. It is a very wide band structure that is basically a folded TEM horn with the aperture ends folded back and terminated with a resistance to prevent reflections. For some applications it has the drawback that the resistive termination reduces the efficiency by about half. This property makes it not useful for a mobile platform where power must be conserved. To increase the low- frequency range and efficiency of the TEM horn, a study was undertaken to look into lossless loading methods.

Baum [8] used the concept of routing a loop around the back of the TEM horn such that the currents introduce a magnetic moment which, along with the electric moment of the horn, channels the radiation in the forward direction. This design also requires a resistive loading of the loop. A detailed theoretical design for this type of antenna is given by Vogel [9]. Liu, Wang, and Wang [10] used the work of Baum and Vogel to construct and test the compensated TEM horn antenna. The design looks like a metal box enclosing an exponential-shaped TEM horn. According to Liu *et al.*, "... with the low-frequency design, the low-frequency point of the −3 dB bandwidth of the response of an ordinary TEM horn to a Gaussian impulse excitation with frequency spectrum centered around 800 MHz has dropped from 400 MHz to 320 MHz, and the −20 dB bandwidth of the antenna increases from around 5:1 to larger than 6:1." These are modest improvements at the expense of decreased radiation efficiency.

Altshuler [11] in the 1960's used a lumped resistance loading to modify a dipole in free space in order to produce a traveling-wave section. This loading was placed one quarter wavelength from the end of the antenna. Thus a traveling wave of current exists from the

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driving point to the load and a standing wave on the end section. The input impedance varied only slightly over a 2-to-1 frequency band. The major drawback was that the antenna was only about 50 per cent efficient. Nyquest and Chen [12] looked into using a nondissipative loading for a loaded linear antenna. The optimum reactance had a value which depended on an optimum end position. With regard to the TEM horn antenna, this design translates into having "two ears" hanging back from the horn and having an active method of changing the load value and position. Although this is possible in theory, the design seems too intricate for a battle-hardened field system. One practical solution is to fix the value of the reactive termination and its end position to achieve some level of broad-banding. It is questionable whether these modifications are worth the effort and, at the very least, they would require some experimental justification.

One modification for the basic TEM horn has some advantages with regard to reducing reflections from the exit aperture. The idea is to use an exponential geometry for the horn [13]. The geometry and the design parameters are shown in Fig. 4.
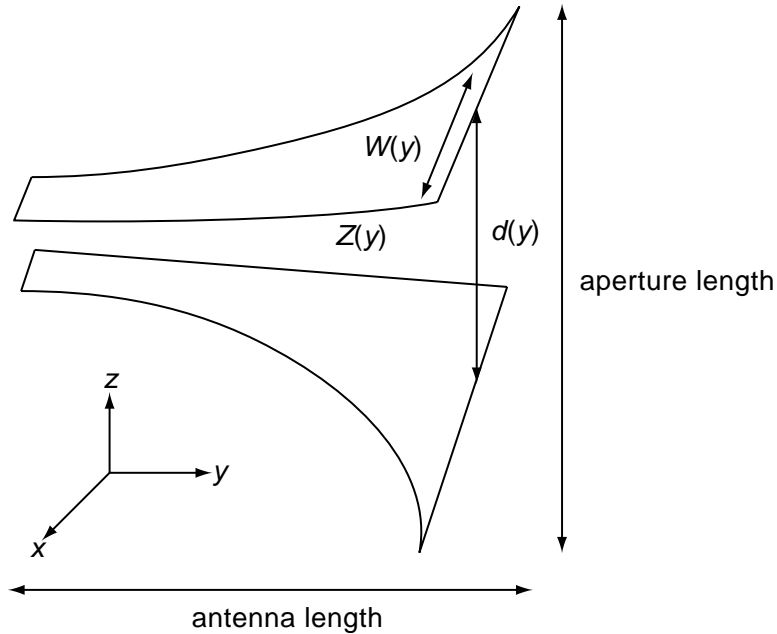

FIG. 4: Design parameters of a TEM horn. Reproduced from Fig. 2 of Chung *et al.* [13].

In order to find the separation between the plates, only three equations are needed. These are taken from [13, p. 230]. First, the equation for the characteristic impedance $Z(y)$ between the two plates in terms of the separation $d(y)$ and the plate width $w(y)$ is

$$Z(y) = \frac{d(y)}{w(y)} \eta, \tag{B1}$$

where $\eta = 120\pi \ \Omega$ is the impedance of free space.

Second, the characteristic impedance at any point along the antenna is given by

$$Z(y) = Z_0 e^{\alpha y}; \qquad (0 \le y \le L), \tag{B2}$$

where

$$\alpha = \frac{1}{L} \ln \left(\frac{\eta}{Z_0} \right),$$

and $Z_0 = 50 \ \Omega$ is the driving-point impedance and L is the antenna length.

Lastly, the separation $d(y)$ between the two plates is given by

$$d(y) = 2\{ae^{by} + c\}; \qquad (0 \le y \le L). \tag{B3}$$

The constants a, b, and c appearing in Eq. (B3) are chosen under the constraint of satisfying the three equations.

APPENDIX C: HEALTH EFFECTS OF ELECTROMAGNETIC RADIATION

Exposure to Electromagnetic Radiation (ER) can produce biological effects that can be harmful to human health. A review of findings on the problems in setting up meaningful standards can be found in a study by Sandler [14] and his colleagues, King and Wu. One problem was to correlate biological damage to the incident field. This calculation cannot be done in a general way since it depends on a number of specific quantities such as: (1) the nature of the source, (2) the electrical distance between the body and the source, (3) the type of radiation (e.g. CW or pulse), and (4) the magnitude of the local fields and power inside the body and organs. Biological damage can be due to thermal effects or field effects, which do not produce heat.

An excellent book on calculating electromagnetic exposure with regards to safety standards is in a book by Ed Hare [15]. This book allows one to calculate RF exposure from a number of different antenna configurations like dipoles and arrays. Some sample calculations are found in Chapter 5, How to Evaluate an Amateur Station. A very large set of tables for different configurations is also provided.

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13. ABSTRACT (Maximum 200 words)
A promising approach to detecting roadside bombs attached to command wires is the electromagnetic sensing and identification of the wires. The lowest five resonant frequencies of the wires, along with the widths of the resonances, can serve as a "fingerprint" for finding the wires. A first large step toward exploiting this fingerprint is to calculate the resonances and their widths for a straight wire on a flat interface between a homogeneous earth and air. The calculation of resonances requires extending the theory of the linear antenna to deal with a wire on the interface between two dielectric media, which we accomplish here. Complex-valued resonant frequencies are defined as those for which a certain homogeneous integral equation for the current in the strip on the interface has non-trivial solutions. By applying a Galerkin procedure we obtain approximate numerical solutions for the resonant frequencies and their widths. We also discuss antenna structures needed to implement an electromagnetic sensor to exploit the resonances for the detection and identification of command wires and give pointers to published material relevant to the analysis of health effects of exposure to electromagnetic radiation.

14. SUBJECT TERMS Improvised Explosive Devices (IEDs); electromagnetic detection of IEDs; electromagnetic propagation over earth; Galerkin method; EMF method; TEM horn antennas; transmission-line antennas			15. NUMBER OF PAGES 20
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Enclosure 1